Acoustic Resonance Classification of Swimbladder-Bearing Fish

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LONG-TERM GOALS

To understand and exploit the resonance scattering by swimbladder-bearing fish (typically in the 1-10 kHz frequency region). Exploitation of the resonances can significantly reduce ambiguities in interpreting acoustic scattering in terms of meaningful biological parameters compared with traditional higher frequency approaches.

OBJECTIVES

To conduct a new class of quantitative acoustic studies of scattering by swimbladder-bearing fish utilizing new commercial broadband-acoustic technology that is optimized for use in the resonance scattering region of fish.

APPROACH

This research is taking advantage of a commercial system that was originally designed for marine geological and gas/oil exploration. It is especially attractive for use in studying swimbladder-bearing fish because this system was optimized for use in the frequency band in which swimbladders typically resonate. The off-the-shelf sensors on the system (in particular, the transmitters and receivers) were selected and configured in a manner best suited for the fish application. The system is being used for studying distributions of fish in their natural habitat. The research is part of a NOAA/NMFS fisheries study and includes trawling for ground truthing and traditional high frequency echo sounders for comparison. Data are being interpreted in terms of physics-based scattering models whose parameters may be determined empirically as a result of the measurements. Tim Stanton oversees the entire program and is involved in every aspect. Dezhang Chu participated in finalizing system specifications, conducting the system calibration, participating in the at-sea study, and processing the data. Mike Jech conducts the biological sampling, performs high frequency acoustic surveys, and is involved in the design and execution of the cruises.

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WORK COMPLETED

The year spanned a wide range of activities, including further calibrating data from the September 2005 cruise, developing a new calibration method, developing a new acoustic scattering model for swimbladder-bearing fish, further data analysis of the September 2005 cruise based on the new methods, preparing for the September 2007 cruise, executing the September 2007 cruise, and writing research manuscripts. Significant advances were made on several fronts. One paper was submitted to a peer-reviewed journal, another paper was drafted, and the results for a third have been completed. There was a profound setback this fiscal year involving losing the original instrument at sea after the tow cable parted. The system was replaced allowing the successful completion of the September 2007 cruise.

1. Further calibration of September, 2005 cruise data. A calibration cruise was conducted on October 9, 2006 to complete the two-cruise (one day each) series of calibrations. The intent of this cruise was to calibrate the system at the deepest depths involved in the September, 2005 cruise (150 m). In this cruise, two different calibration spheres were used, suspended under the towbody one at a time, to provide a standard signal by which the system could be calibrated. Most of the way into the measurements, the cable parted and the system was lost. A subsequent recovery cruise was unsuccessful in finding the system. Fortunately, enough data had been collected on the calibration cruise to complete data analysis of the September, 2005 cruise.

2. Development of new calibration method for broadband systems. In our attempt to use standard spherical targets in calibrating the system, it was apparent that the system spanned multiple resonances of the sphere of the frequency band of each channel. The effects of the resonances were especially significant for the highest frequency channel. Smoothing over the resonances resulted in up to 3 dB errors. To address this, we developed a new method to calibrate broadband systems. This new method involves completely eliminating the source of the resonances through time-domain processing. The results are general and can apply to any broadband active system. A paper was submitted this year describing the new method.

3. Development of new hybrid scattering model for swimbladder–bearing fish. In our attempt to use an existing hybrid scattering model to interpret the data, we discovered several deficiencies. The candidate model was the Kirchhoff-Ray-Mode (KRM) model which connects a model that describes the resonance phenomenon at low frequency scattering to a model that describes the high frequency scattering. Significant developments have taken place since that model was originally developed in both frequency regions. Building on the KRM concept of connecting two models, one for each region, we replaced the low and high frequency components with more advanced components from the literature, resulting in a new hybrid model. The swimbladder is modeled as a prolate spheroid in each frequency region, resonance is accounted for in the low frequency region, and tilt angle distribution (through deformed cylinder formulation) is accounted for in the high frequency region. The results of the modeling are given in Fig. 1.

4. Estimating fish density using resonance classification data. The calibration and modeling are applied to the data from the September, 2005 cruise to estimate fish density of a number of patches (Fig. 2). The resonance frequency of 3.7 kHz indicates that the fish are swimbladder-bearing. We observed that the resonance frequency in each patch was approximately the same (3.7 kHz), indicating that all of the fish are of similar size. Since orientation doesn’t affect the scattering at these

frequencies, then the variations in echo levels are due principally to variations in numerical density of fish. Because of these factors, the estimates of fish density have significantly fewer ambiguities than use of traditional high frequency methods.

5. Preparing for September, 2007 cruise. Because of the unfortunate loss of the original system, part of the preparation involved purchasing a new system. Through this process, we were able to significantly reduce a problem that had plagued the original system. In that system, there had been a significant ringing of the lowest frequency transducer. This ringing prevented obtaining data within about 25 m of the device. While fabricating the new system, the manufacturer addressed the issue by using mechanical isolation mounts to install the transducer. The mounts appeared to have solved the problem since the new system has a normal amount of ringing and can detect targets as close as about 12 m. The new system was put through tow tests and was calibrated both at sea during a test cruise and at dockside. One fabrication defect in the system was detected toward the end of the preparation, which involved an inability of the communication electronics to "drive" the long tow cable. As a result, there was the presence of narrowband noise in the data. The noise was sufficiently narrow that most of it can be filtered out in post-processing. The hardware issue will be addressed before the next cruise.

6. Conducting September, 2007 cruise. During the period September 5-14, 2007, the R/V Endeavor was used for our studies of fish. Multiple transects were conducted in both the Georges Bank and Jeffereys Ledges areas in the Gulf of Maine. One transect involved most of the length of Georges Bank along a depth contour of 100 m. Other transects involved zigzag patterns traversing across rapid changes in depths of both areas. Significant differences in fish behavior were observed between the two regions. Georges Bank contained a series of dense patches of fish and the fish at Jeffereys Ledge were generally dispersed with some group behavior.

The measurements involved towing the broadband acoustic system either near the surface or near the seafloor. In the latter case, fish residing near the seafloor were imaged at high resolution, revealing their spatial distribution at the inter-fish level (Fig. 3). In addition to the new broadband system, a traditional high frequency system was towed near the surface for intercomparison between the two systems. Also, after each area was surveyed, an acoustic lens imaging system (Didson lens) was deployed to near the seafloor so that near-bottom fish could be studied (Fig. 4). Lengths of fish and fish-fish and fish-seafloor distances were measured in a small sample volume with that system.

RESULTS

1. New method for calibrating broadband system. This new method allows a broadband system to be calibrated with a single calibration sphere. The key element in the method involved eliminating the source of resonances in the sphere echo through time-domain processing, which, in turn, eliminated the principal source of error associated with standard target calibration. This method is accurate, general, and applicable to any broadband system.

2. New acoustic scattering model. This model describes the scattering by swimbladder-bearing fish over a wide range of frequencies. The model accounts for the resonance at low frequencies as well as tilt-angle distribution at high frequencies. This new model provides a reasonable description of our data over a wide range of frequencies (1-100 kHz) and is written in a general form to apply to other types of fish at other frequencies.

3. Estimates of fish density. Through use of the resonance classification method, fish density was estimated in each of the patches. Because of the use of resonance classification and the fact that the frequencies are low (and hence fish orientation is not a factor), the results have significantly fewer ambiguities than use of traditional high frequency methods.

4. High resolution methods illustrating fish size and behavior.

a. Fish size. Through use of the high resolution acoustic lens system deployed near the fish, fish size and, to some extent, behavior were observed directly in the images. The sampling volume is relatively small, only showing 1-2 fish at a time. This is a powerful technique, to be used in concert with nets and acoustic survey systems to make direct measurements of the fish size without concern of net avoidance or any ambiguities associated with survey acoustics.

b. Fish behavior. Through a combination of towing the broadband acoustic system near the fish (at 150 m depth) and broadband signal processing (pulse-compression processing), high resolution images of fish distributions were obtained at the inter-fish level. This approach complements the lens system in 4a as an entire school or shoal can be imaged (but at lower resolution so that one fish is a single "pixel"). This is also a powerful technique, as the change in inter-fish spacing can be determined as a function of distance along transect (and, hence, as a function of environmental features such as bathymetry).

IMPACT/APPLICATIONS

There is potential impact in several major categories, all involving broadband active acoustic systems. We have developed and applied a new calibration method and acoustic scattering model for use in interpreting broadband acoustic scattering data from swimbladder-bearing fish. As a result, acoustic studies of swimbladder-bearing fish can be significantly more accurate through use of resonance classification than ones using traditional high frequency methods. The methods are general. The calibration method is applicable to any broadband system and the scattering model is applicable to a wide range of types of fish. Also, through the combination of towing the system deep near the fish and pulse-compression processing, the system is providing unique data concerning inter-fish spacing over large distances. This approach is general and has potential for providing new understanding of fish behavior.

RELATED PROJECTS

We are being funded through the Undersea Signal Processing Division of ONR to study the statistics of the echo amplitudes (grant N00014-07-1-0232). Currently the statistics have been studied in relation to a combination of the patchiness of the fish and acoustic beampattern. The studies show that the echoes are strongly non-Rayleigh which may need to be accounted for in ASW systems. Several probability density functions (PDF's) have been used or developed to describe the statistics.

PUBLICATIONS

Stanton, T.K., Chu, D., Jech, J.M., and Irish, J.D. (2007) "A broadband echosounder for resonance classification of swimbladder-bearing fish," Proceedings of the IEEE Oceans 07 Conference (Aberdeen).

Stanton, T.K. and Chu, D. (submitted). "Calibration of broadband active acoustic systems using a single standard spherical target," J. Acoust. Soc. Am. (refereed).

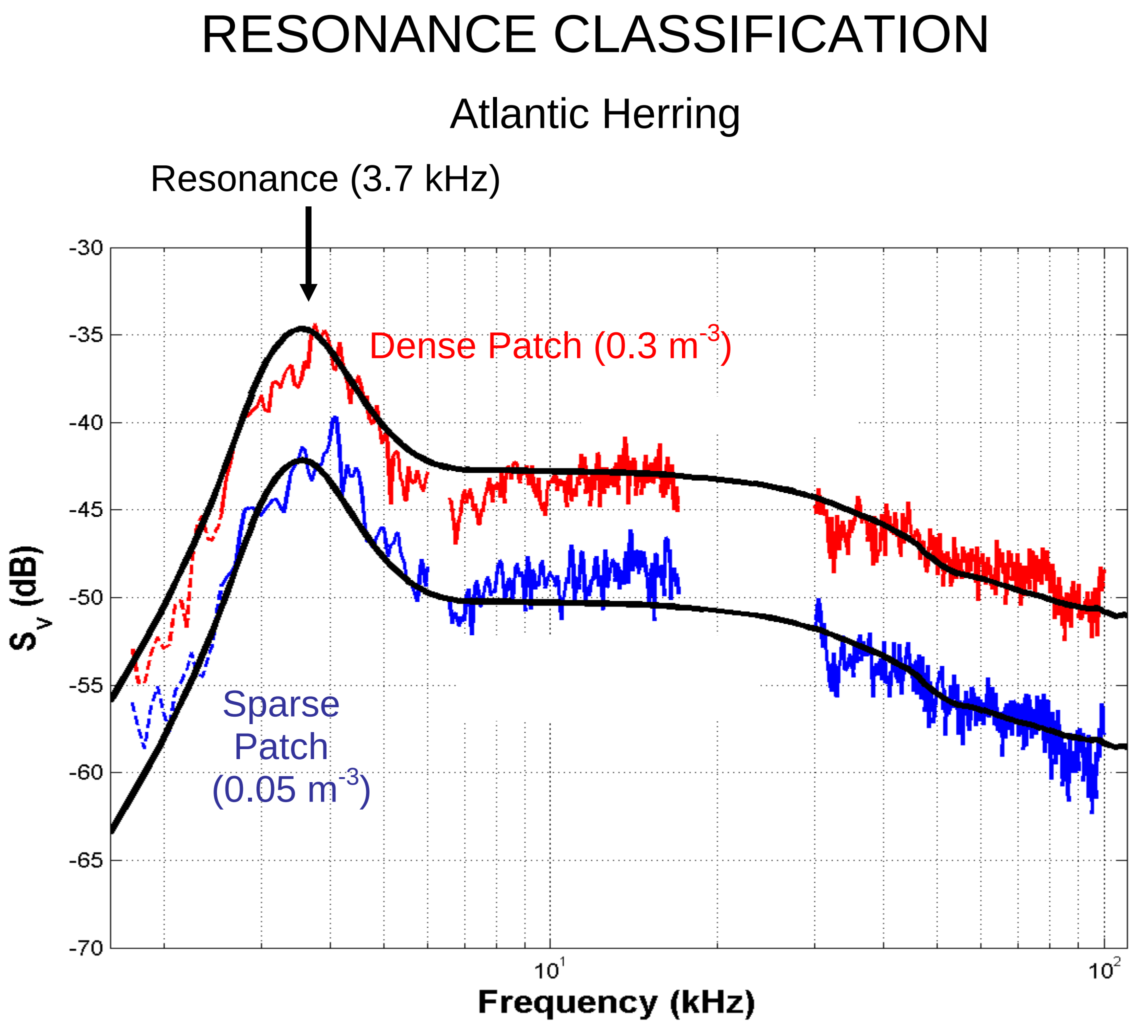

Figure 1. Volume scattering strength from dense and sparse patches of Atlantic Herring, as measured in our September, 2005 cruise. The data are calibrated through a combination of standard sphere method (full wave) and an advanced calibration method (partial wave) developed in this project, allowing for accurate calibration over the two decades of frequencies. The model, which spans the full range of frequencies, is a hybrid model developed in this project accounting for both the resonance characteristics of the swimbladder at the lower frequencies and the tilt-angle distribution of the fish at the higher frequencies. The data show the resonance frequency to be the same for each patch indicating that the change in overall level is due to a change in numerical density of the fish.

ESTIMATES OF FISH DENSITY

Using resonance classification at 2-6 kHz

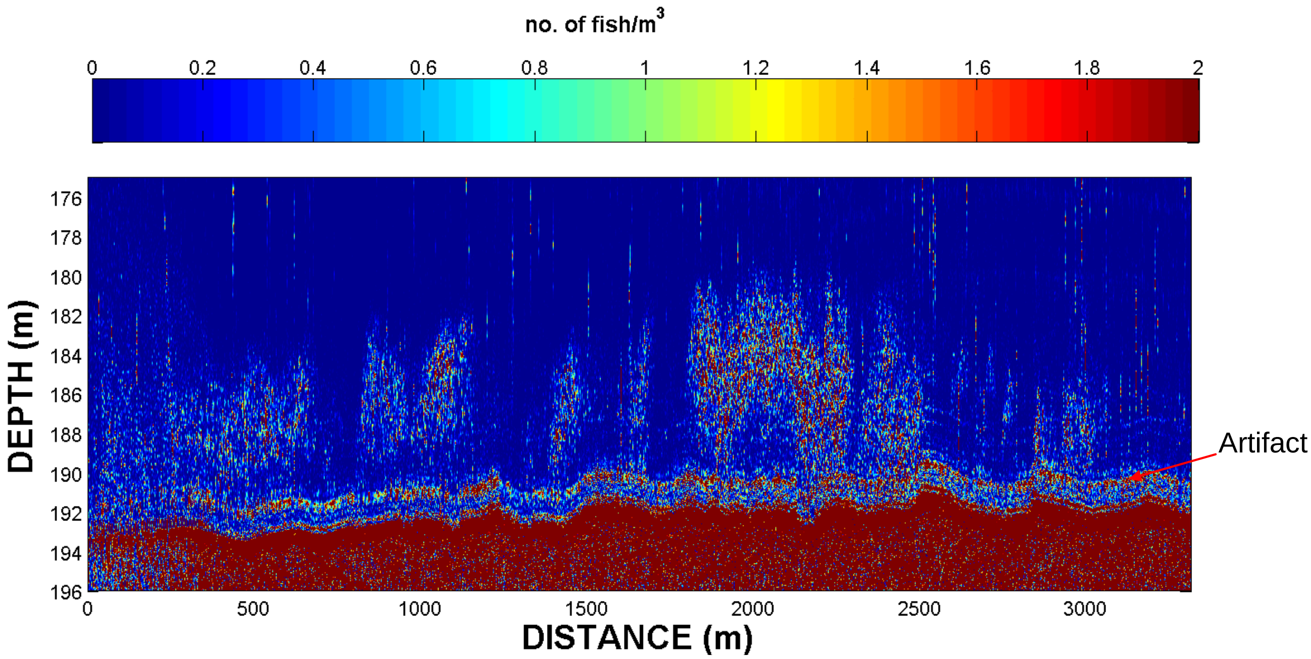

Figure 2. Estimates of fish density (Atlantic Herring) using acoustic resonance classification. This is the "product" of the combination of measurements of broadband acoustic scattering by swimbladder-bearing fish, calibration of the system at the same depth at which it was towed (150 m), and development of the new acoustic scattering model. The estimates take advantage of the fact that the resonance frequency of each patch shown is approximately the same, indicating that the change in echo level is due solely to change in numerical density (Fig. 1). Because of the resonance information and the fact that orientation does not affect the scattering at these low frequencies, the ambiguities in these estimates are significantly lower than use of traditional high frequency sound.

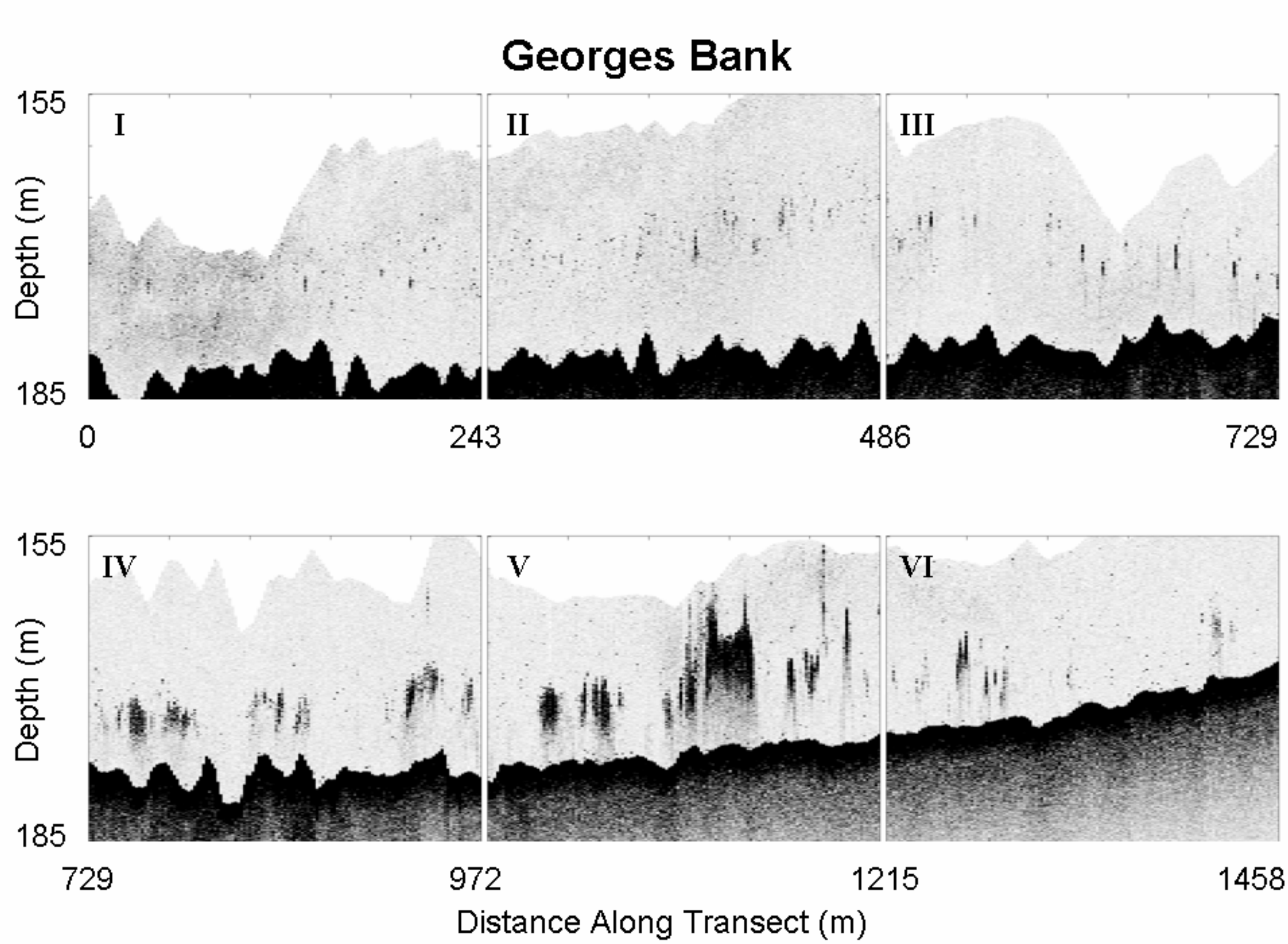

Figure 3. High resolution acoustic survey of fish distribution in September, 2007 cruise. Through a combination of towing the broadband system deep near the fish and broadband signal processing (pulse-compression processing), the system provides high resolution images of fish. In this case, each dark pixel represents an individual fish. Each dark patch is a patch of fish. This example shows a transect over Georges Bank in which the fish are initially dispersed ("I") and eventually form patches of increasingly large size ("IV" and "V"). The image was formed using a 50-110 kHz broadband system. The large patches also resulted in significant echoes in the 1-5 kHz channel, with an acoustic "signature" consistent with swimbladder-bearing fish (probably Atlantic Herring).

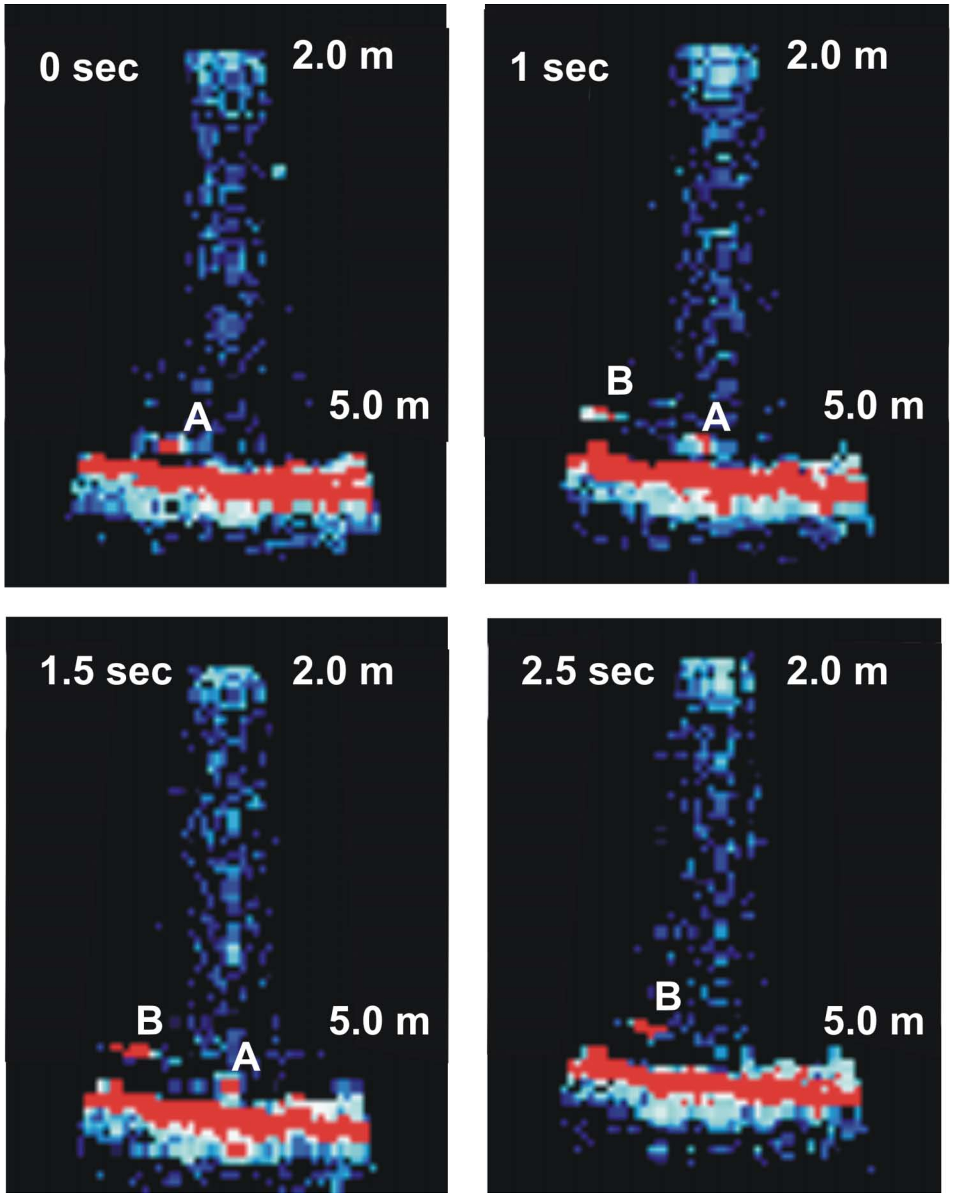

Figure 4. Imaging of fish near seafloor with acoustic lens. In the September, 2007 cruise, a Didson acoustic lens imaging system was lowered to near the seafloor to obtain high resolution images of fish near the seafloor. A sequence of four images shows two fish swimming through the field of view near the seafloor, which is the large elongated red patch at the bottom of the image. Fish "A" and "B" are estimated from the images to be 40 and 44 cm in length, respectively, and are believed to be haddock, based on historical trawl data.